Quantum Hall and Insulating States of a Broken-gap 2-D Electron-hole System

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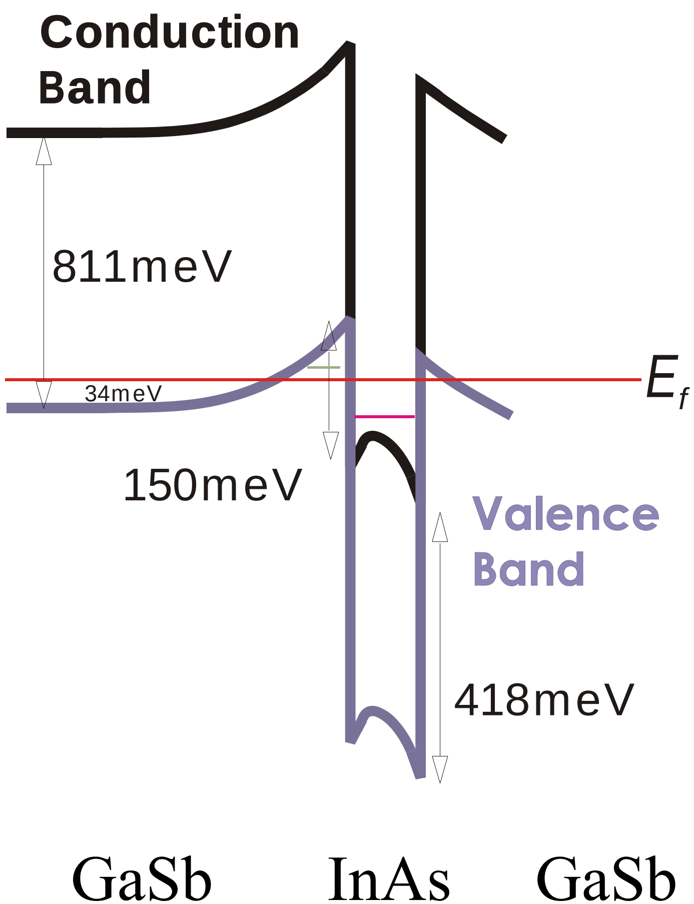
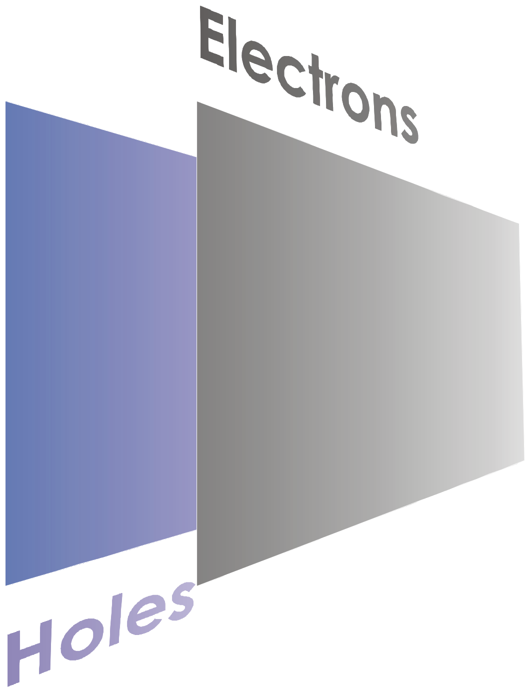
Talk Outline

- Insulating states $\sigma_{xx} = 0;\ \sigma_{xy}^{\mathrm{net}} = \sigma_{xy}^{\mathrm{e}} + \sigma_{xy}^{\mathrm{h}} = 0$
  - Novel behaviour
  - Edge-channel conduction [Physica B 298 28 (2001)]
  - Magnetoconductance fluctuations
  - In-plane magnetic field

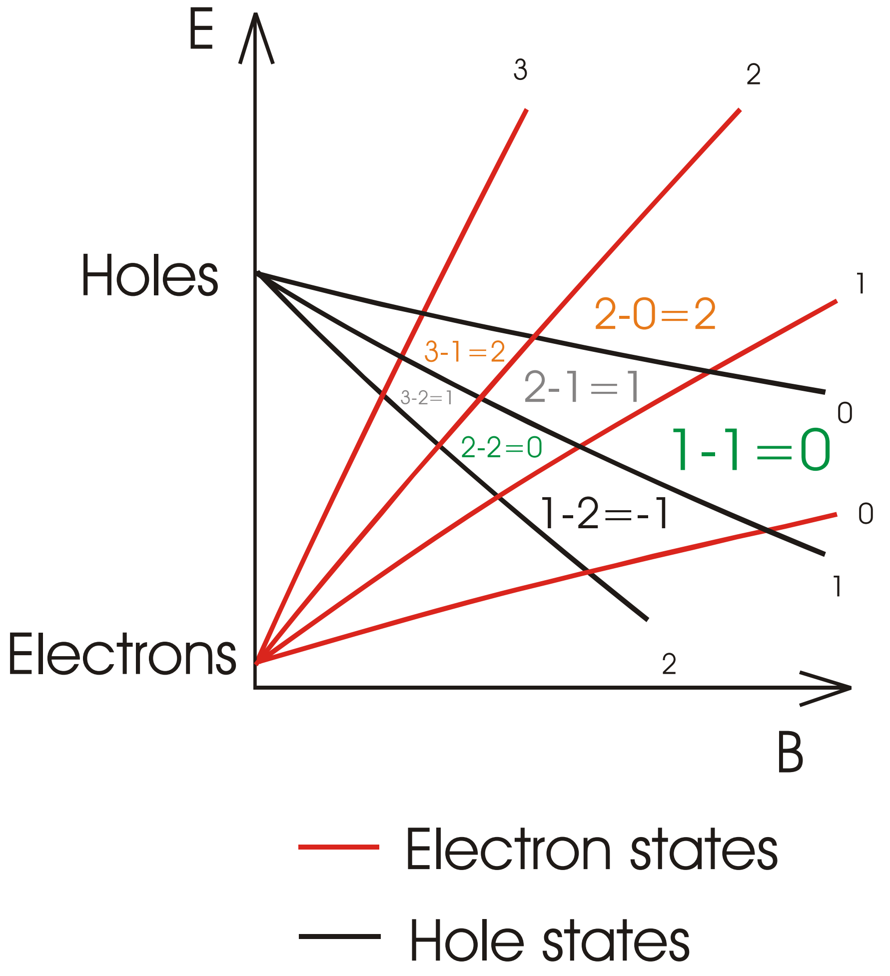
- Quantum Hall states $\sigma_{xx} = 0;\ \sigma_{xy}^{\mathrm{net}} = \sigma_{xy}^{\mathrm{e}} + \sigma_{xy}^{\mathrm{h}} \neq 0$
  - Breakdown and current dependence [Physica B 298 8 (2001)]
  - Width dependence

InAs/GaSb Broken Gap System





Landau levels in magnetic field



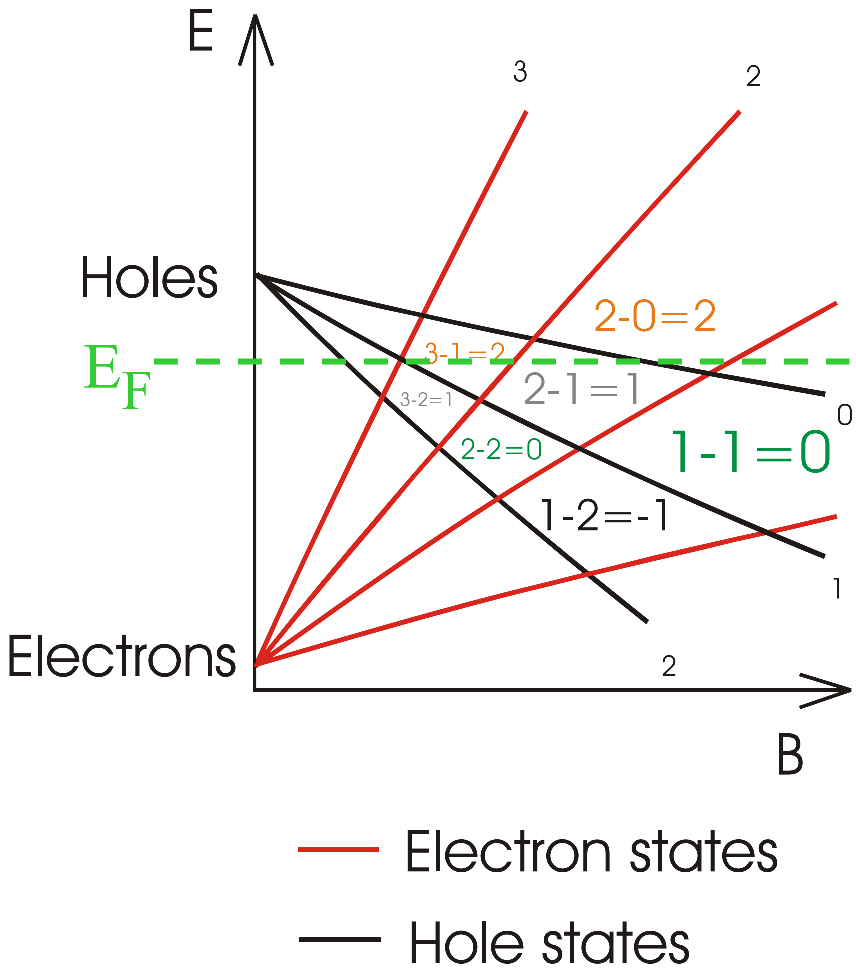
Behaviour of quantized Hall conductance:

$$R_H = -h/e^2(\nu_e - \nu_h)$$

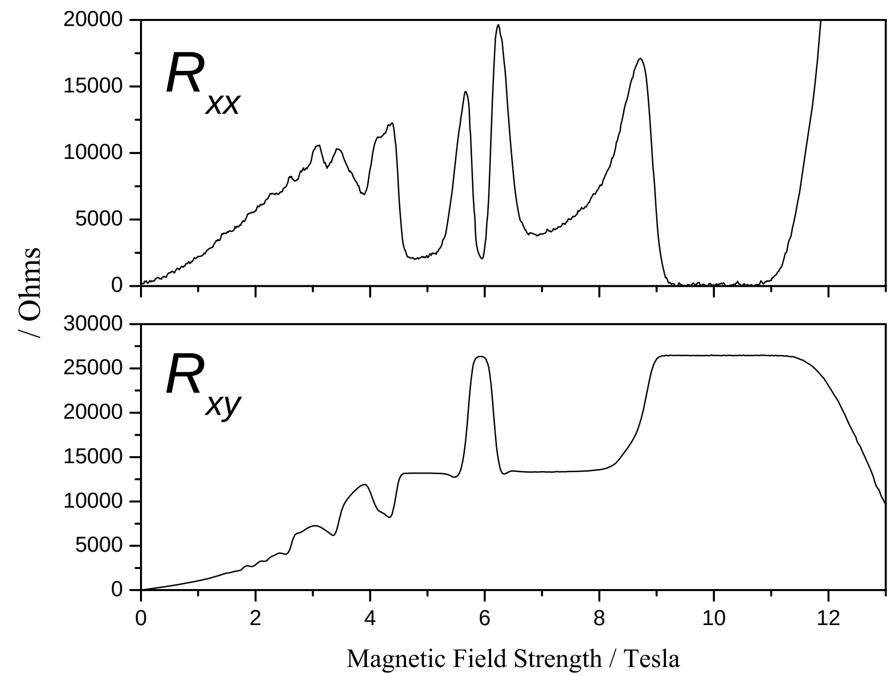
consistent with $\sigma_{net} = \sigma_e + \sigma_h$

[Mendez et al., PRL **55** 2216 (1985)]

Landau levels in magnetic field



Compensated Quantum Hall Effect

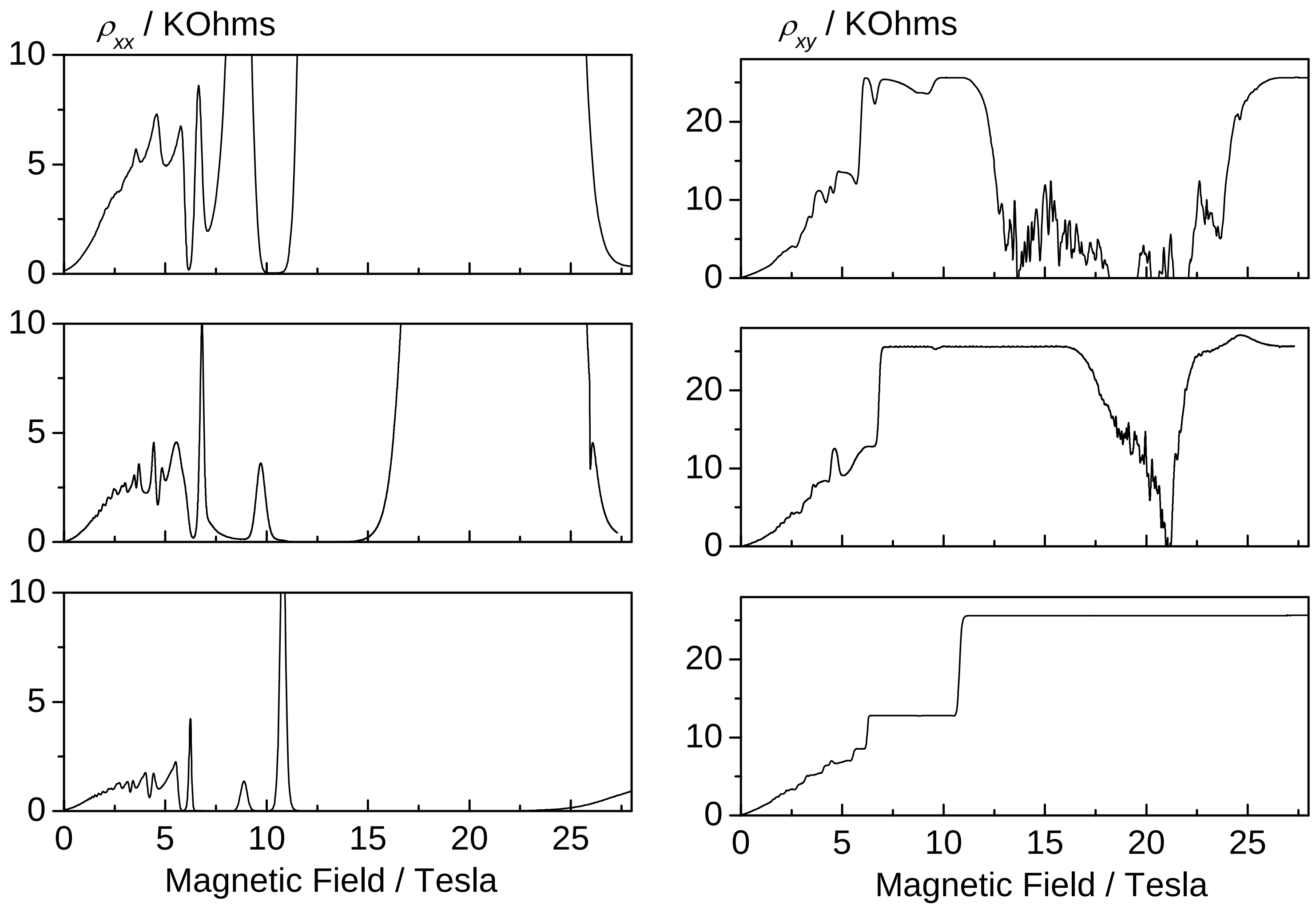


Insulating state forms with increased n_h

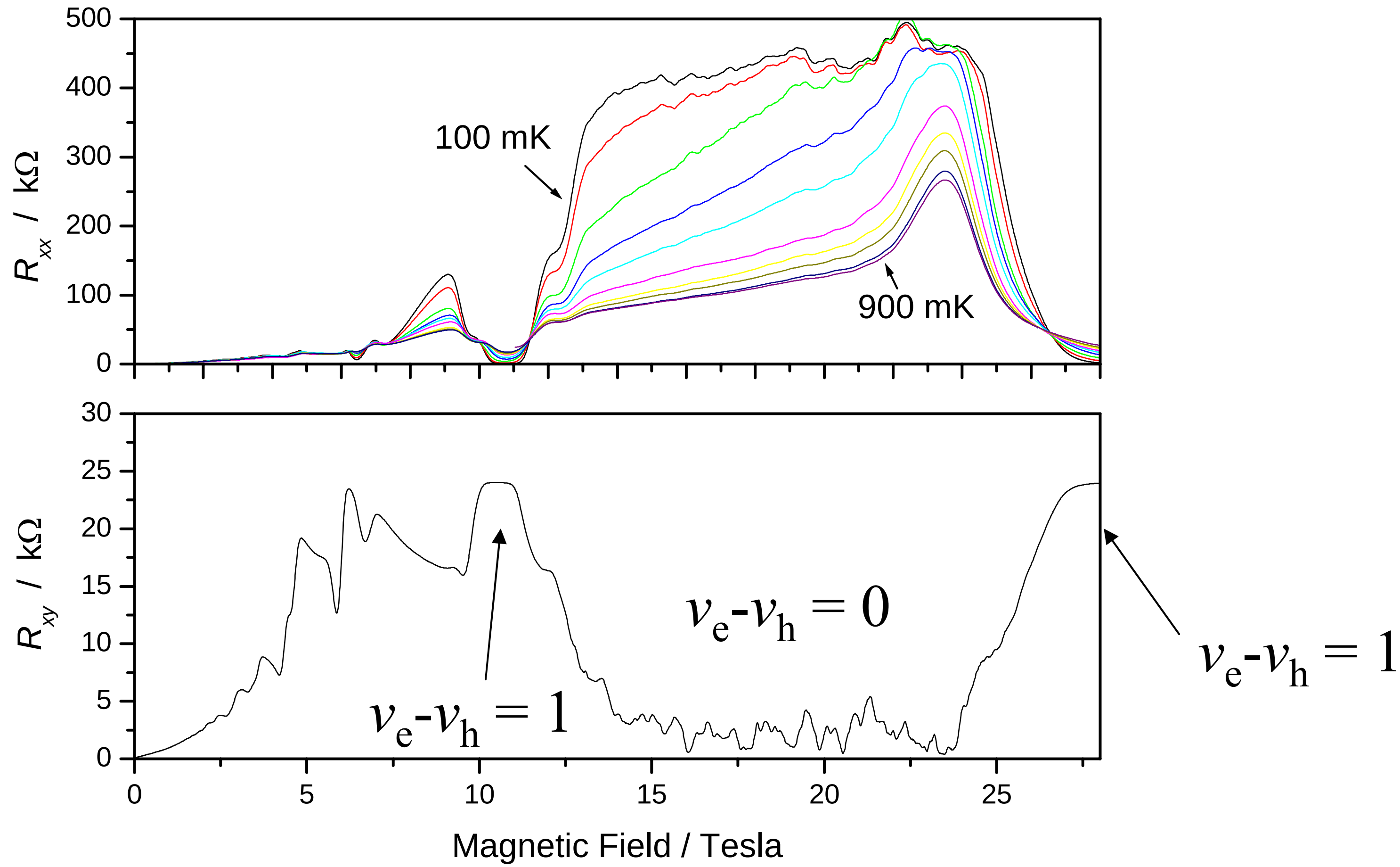
$n_e = 7.9$,
$n_h = 6.1 \times 10^{11} cm^{-2}$

$n_e = 8.0$,
$n_h = 5.2 \times 10^{11} cm^{-2}$

$n_e = 7.8$,
$n_h = 3.7 \times 10^{11} cm^{-2}$

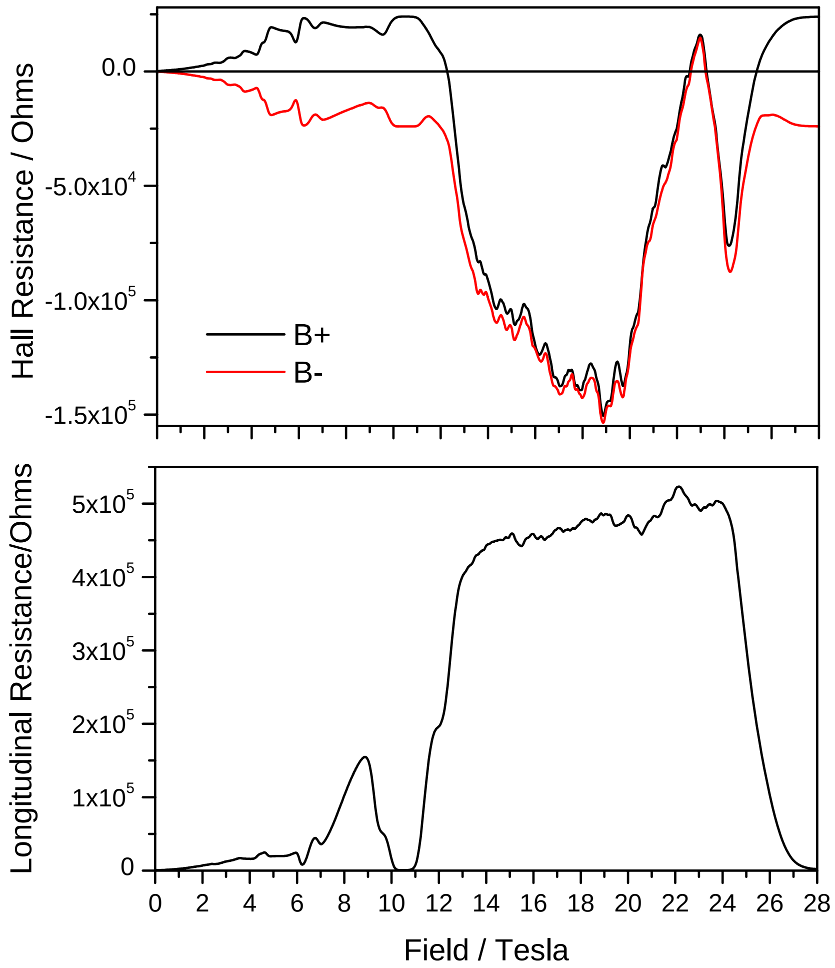


ρ_{xx} oscillates between 'metallic' and 'insulating' behaviour



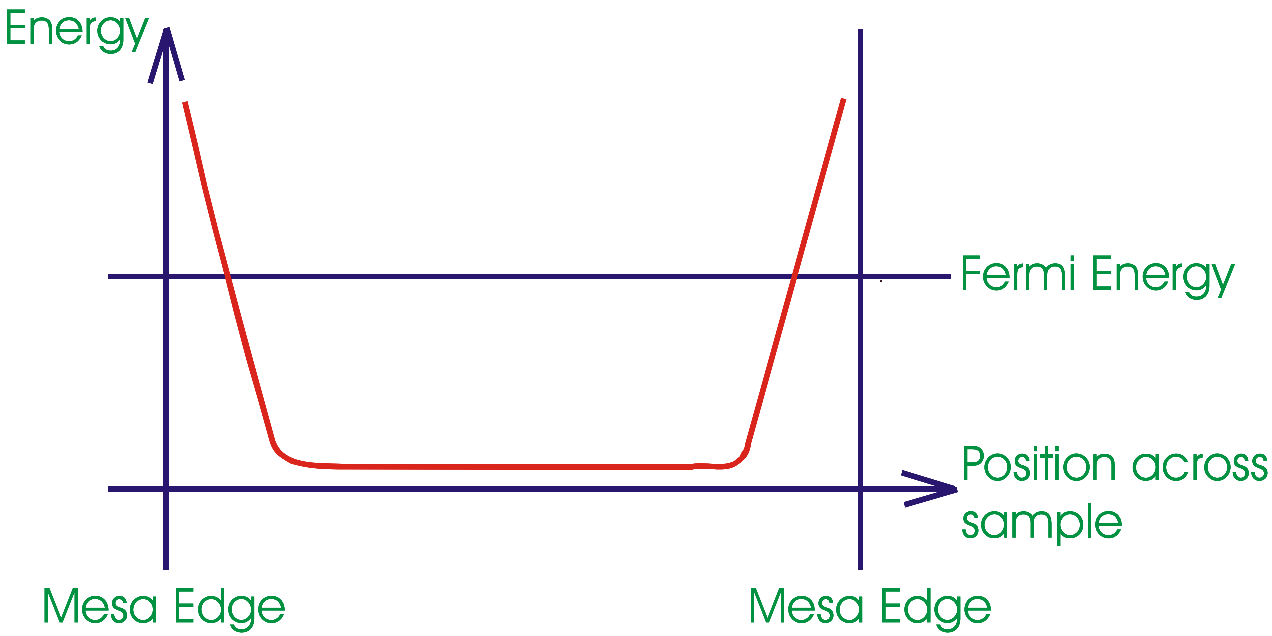
[Nicholas et al, PRL **85** 2364 (2000)]

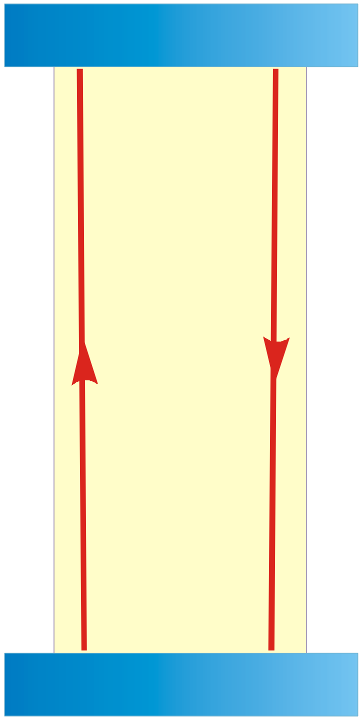
Insulating state: $\nu_e - \nu_h = \mathbf{0}$



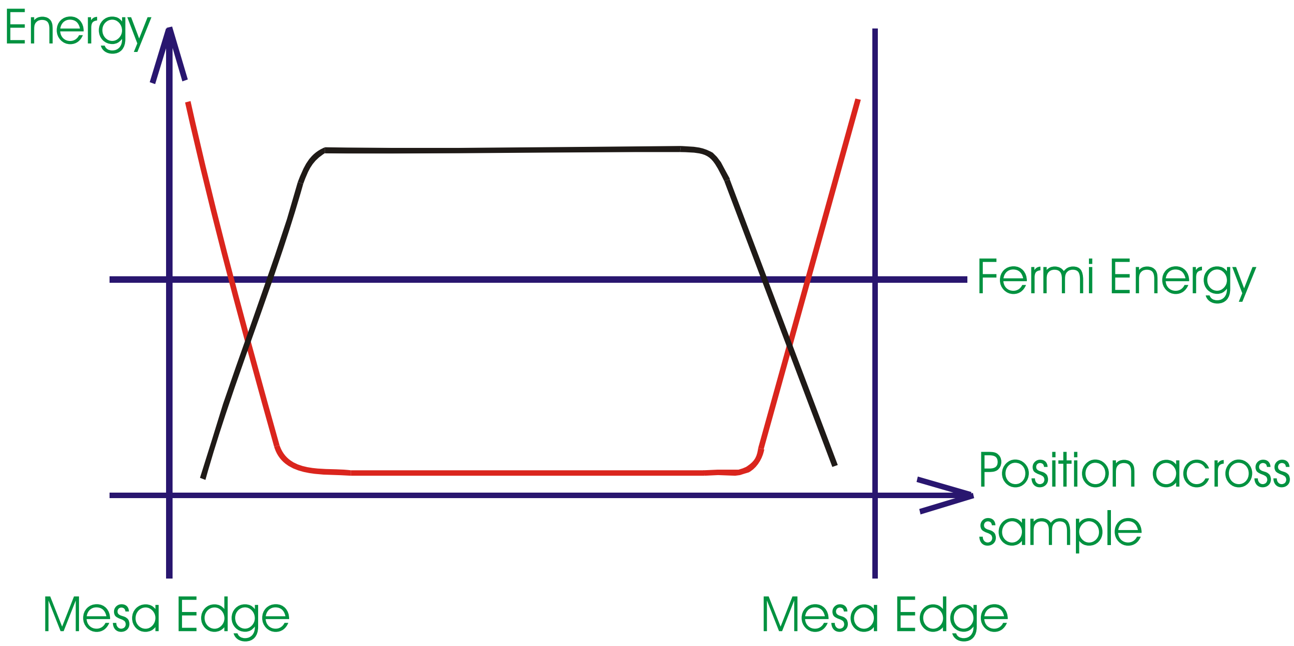
- The Hall resistance becomes symmetric under field reversal.
- Values larger than 50% of ρ_{xx} (R_{xx}/sq.).
- No functional relation with R_{xx}.
- Reproducible fluctuations.
- Macroscopically large samples.

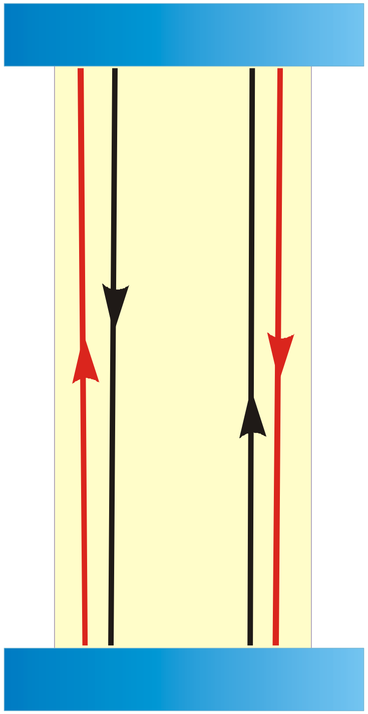
Electron edge states



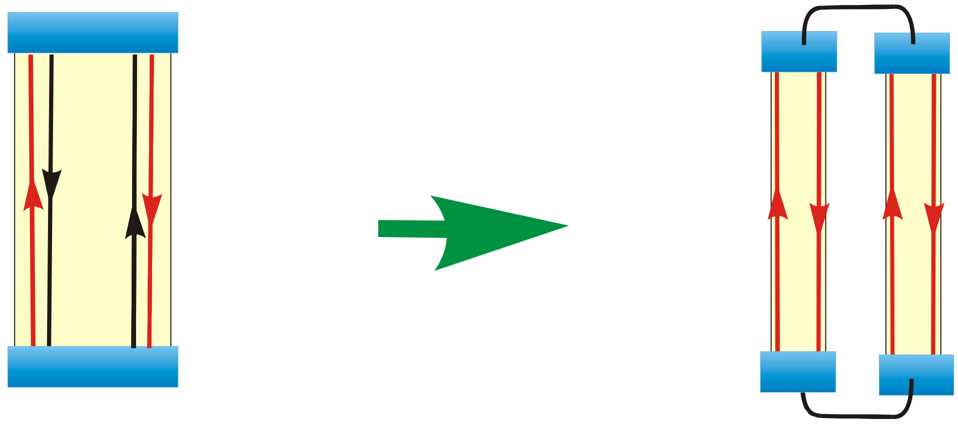


Holes: Counter-propagation

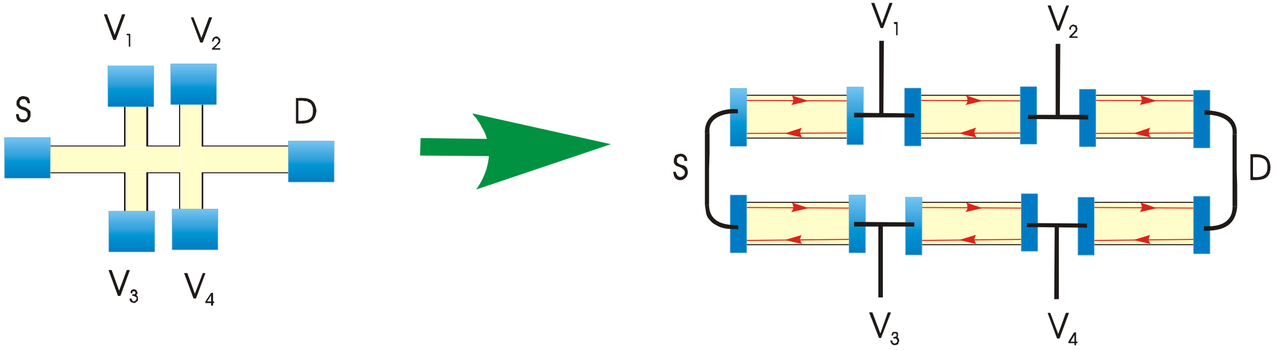




Draw system in terms of single carrier type $\nu = 1$ bars.

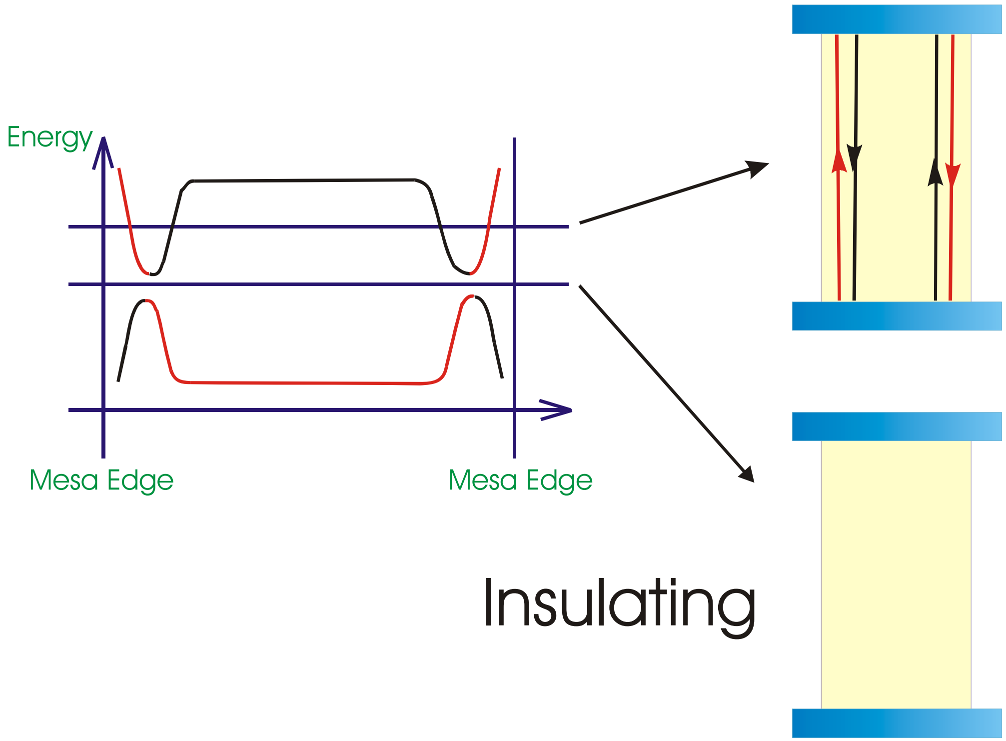


Equivalent circuit for Hall bar:



A measured longitudinal resistance would give $R_{xx} = (V_1 - V_2)/I_{SD} = h/2e^2$

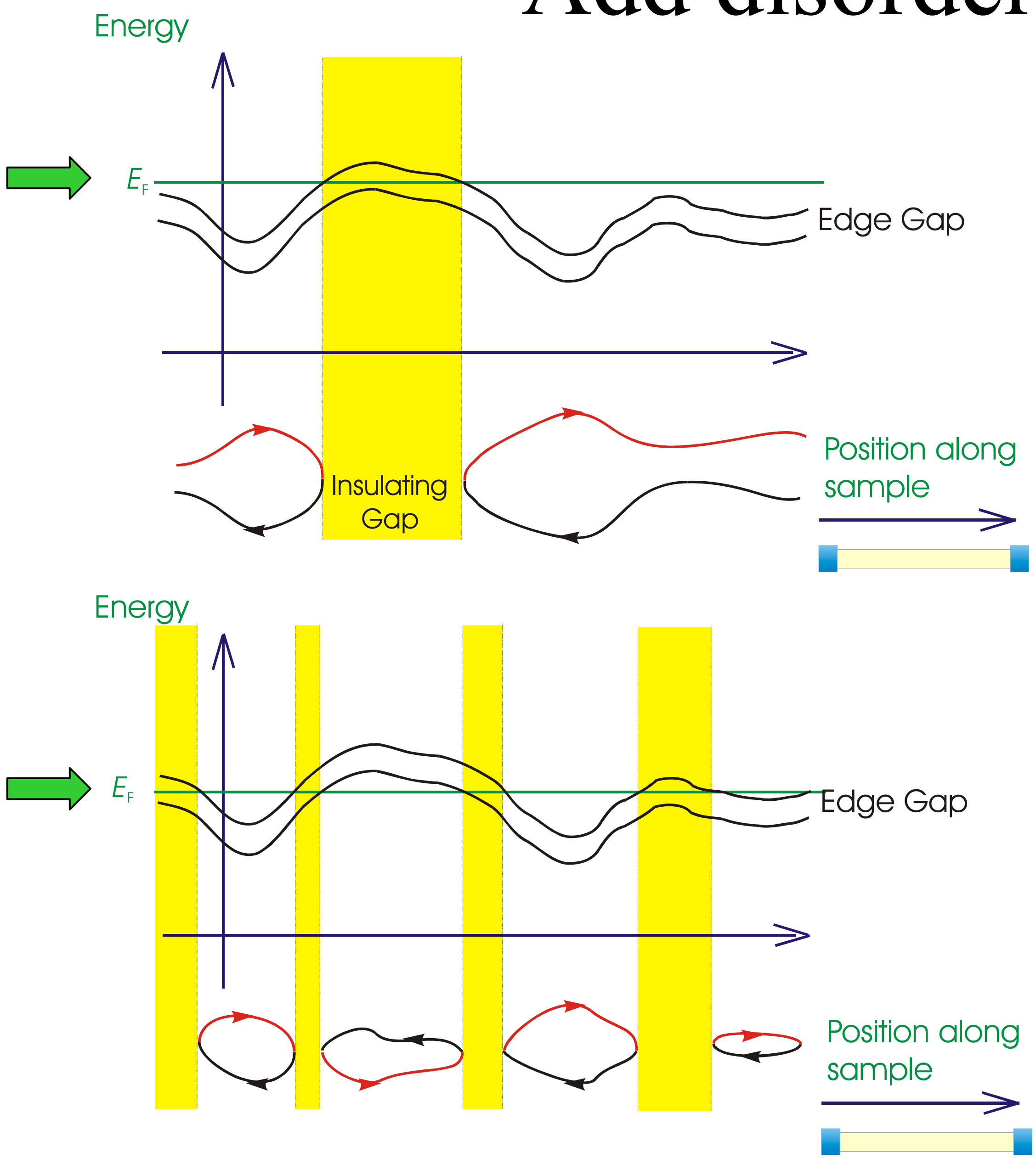
Interactions and Anticrossing



No interactions & scattering = no insulating behaviour.

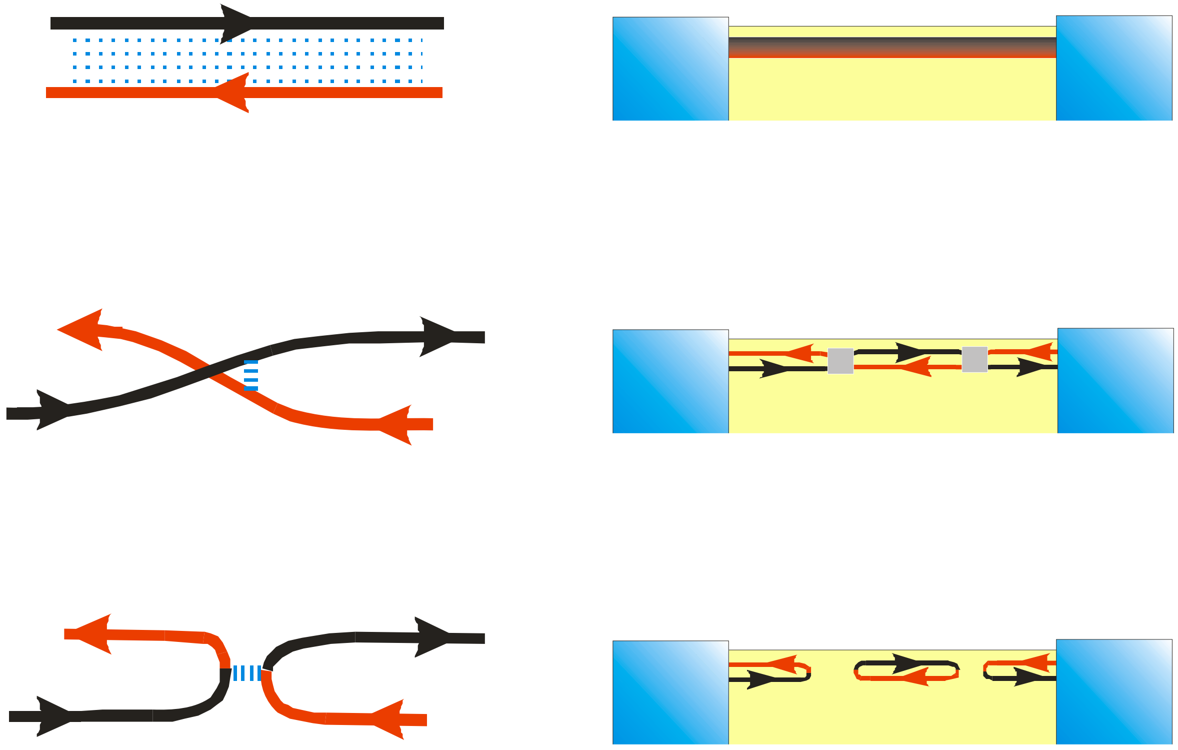
Strong interactions = Completely insulating.

Add disorder

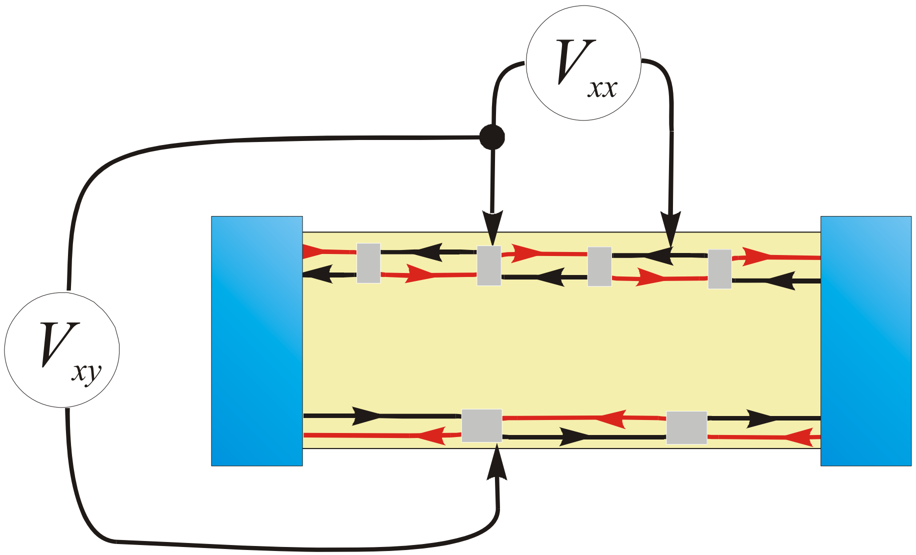


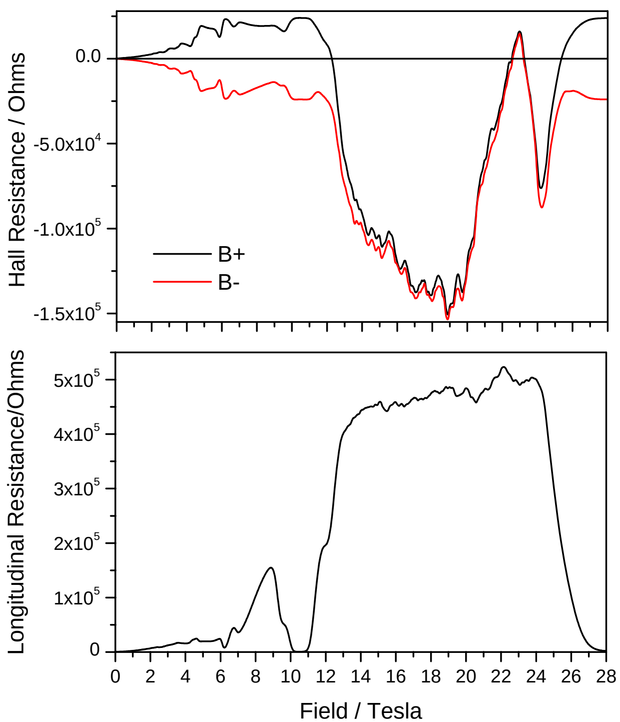
- Gaps may form where E_f cuts the gap.
- Changing the magnetic field moves the gap in energy.
- The Fermi energy cuts the gap at different positions in space.

Conduction depends on strength of interactions and disorder



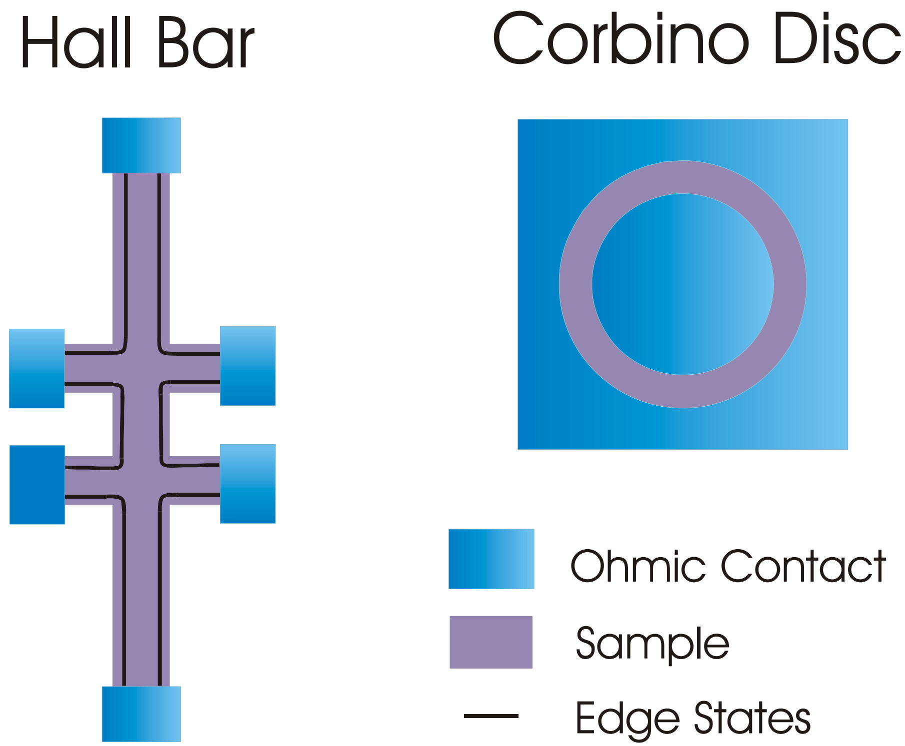
Global Picture



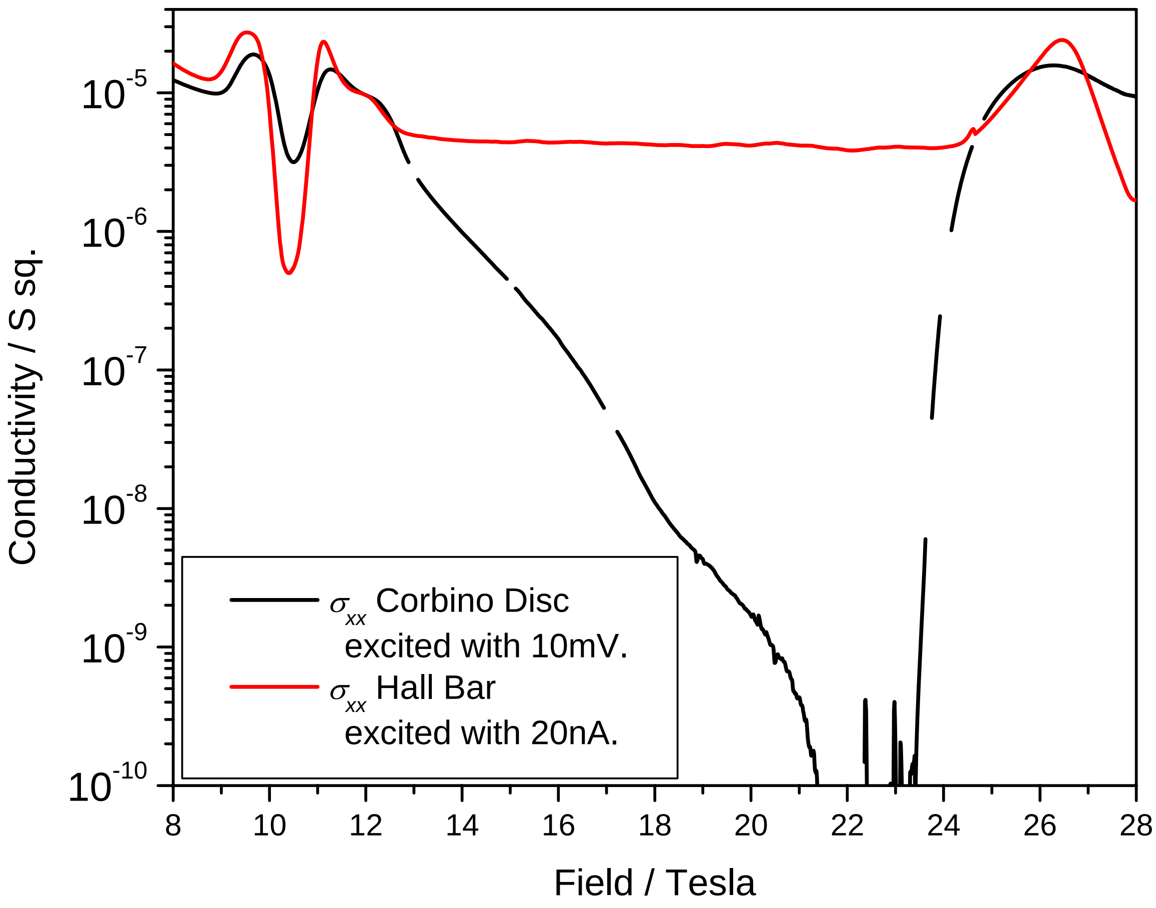


- Potential dropped **between** sections.
- Arrangement depends on disorder and **LL energy**.
- Symmetric Hall resistance.

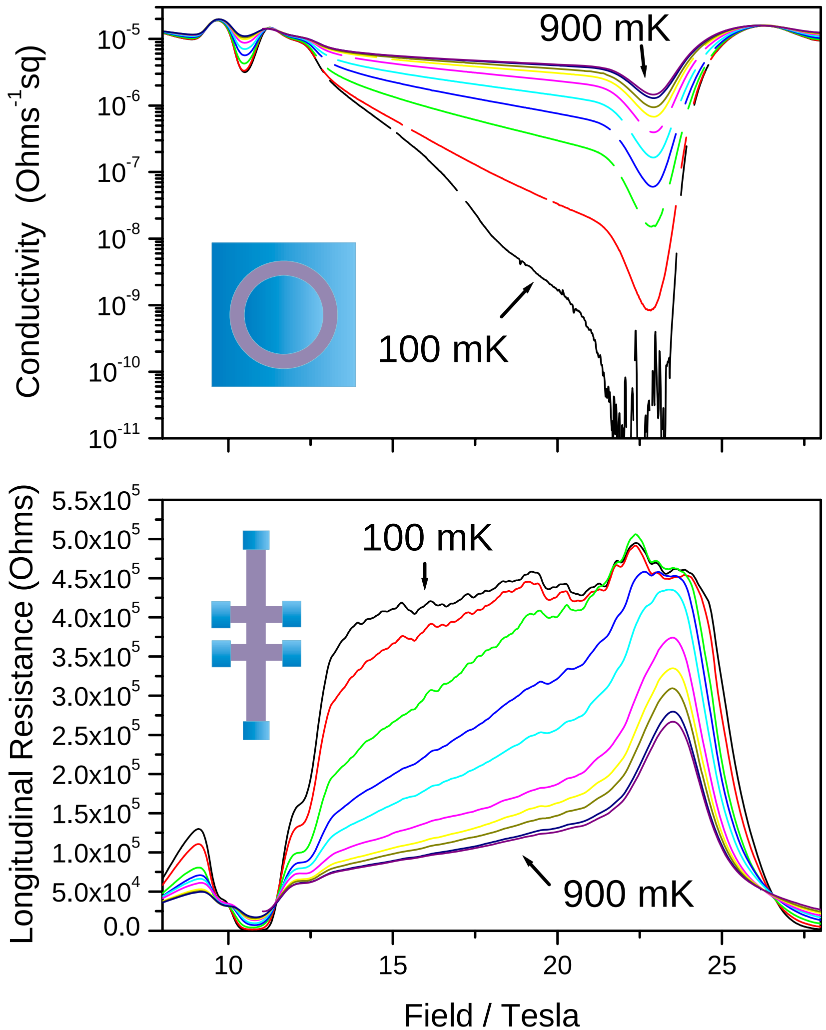
Geometry effects - No Edge State connections for Corbino Disc



Directly Compare Conductivity



Temperature Dependence



- Hall bar resistance saturates at low temperature.
- Corbino disc continuously insulating.
- No fluctuations in Corbino disc data.
- Data reconciled with.

$$\sigma_{xx}^{Hall} = \sigma_E + g\sigma_B.$$

Edge Channel Properties

What we have shown so far:

- Edges contribute conductance with fluctuations.
- Edge-states must be drastically altered.

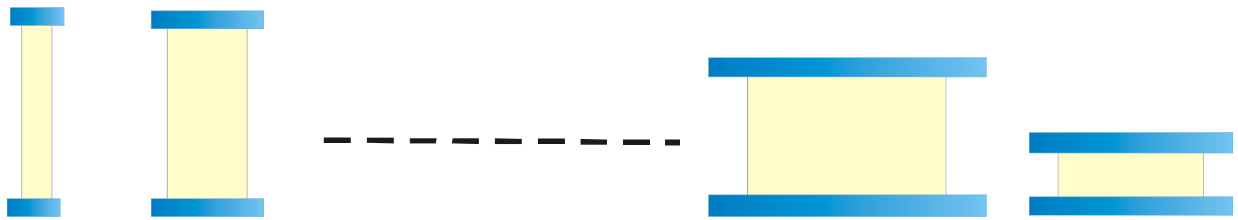
Immediate questions:

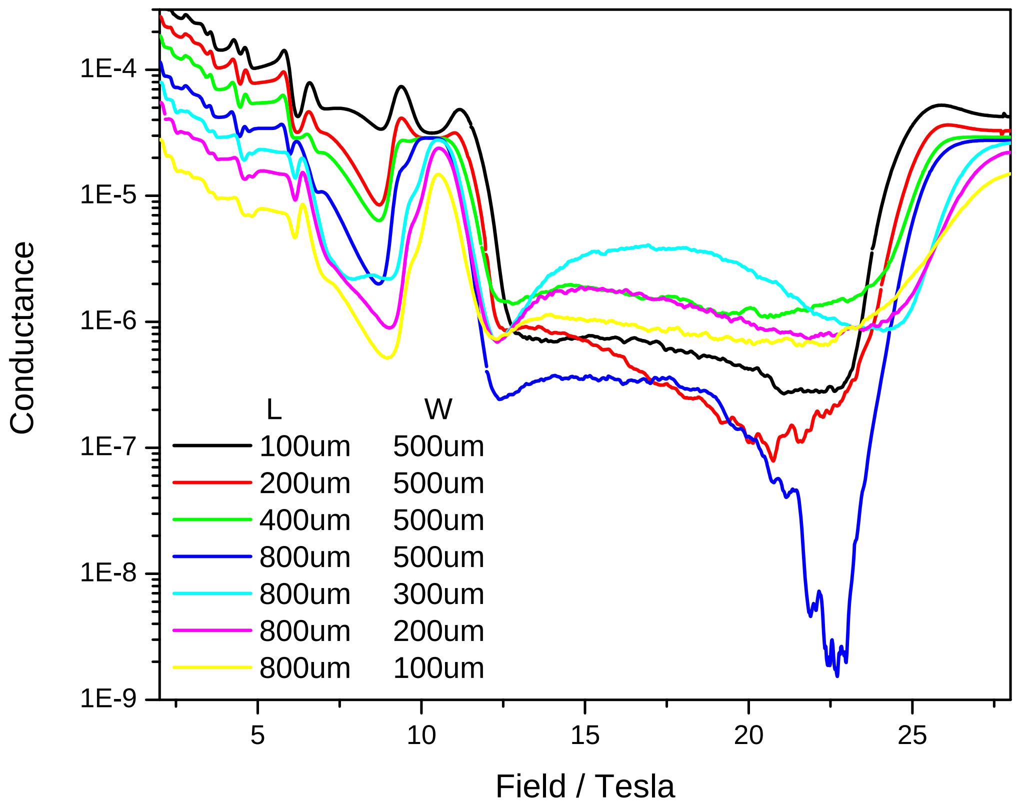
- Fluctuations – Energy or Phase effect?
- Is the conduction really affected by interactions between e and h edge states?

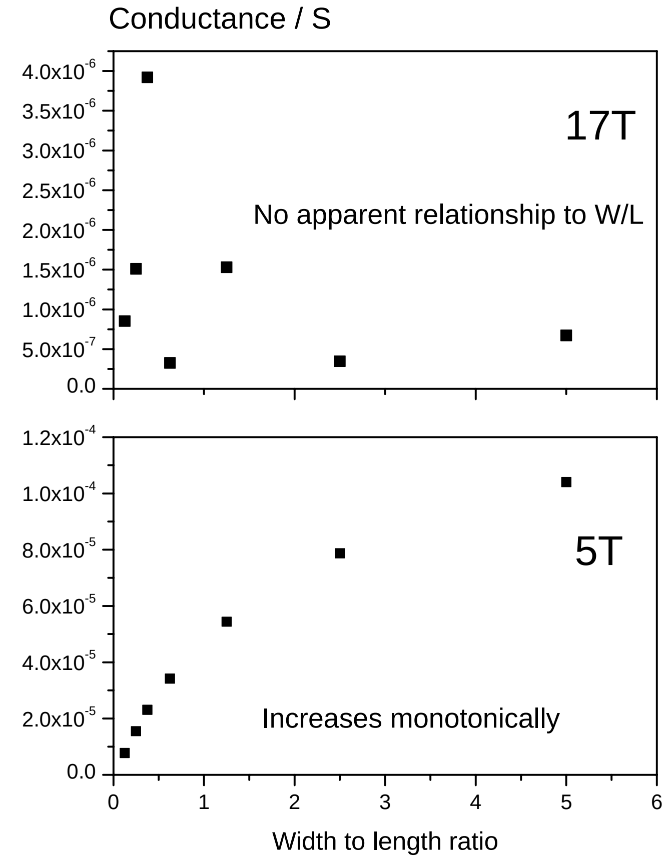
Look at dependence on:

- Width and Length
- In-plane magnetic field

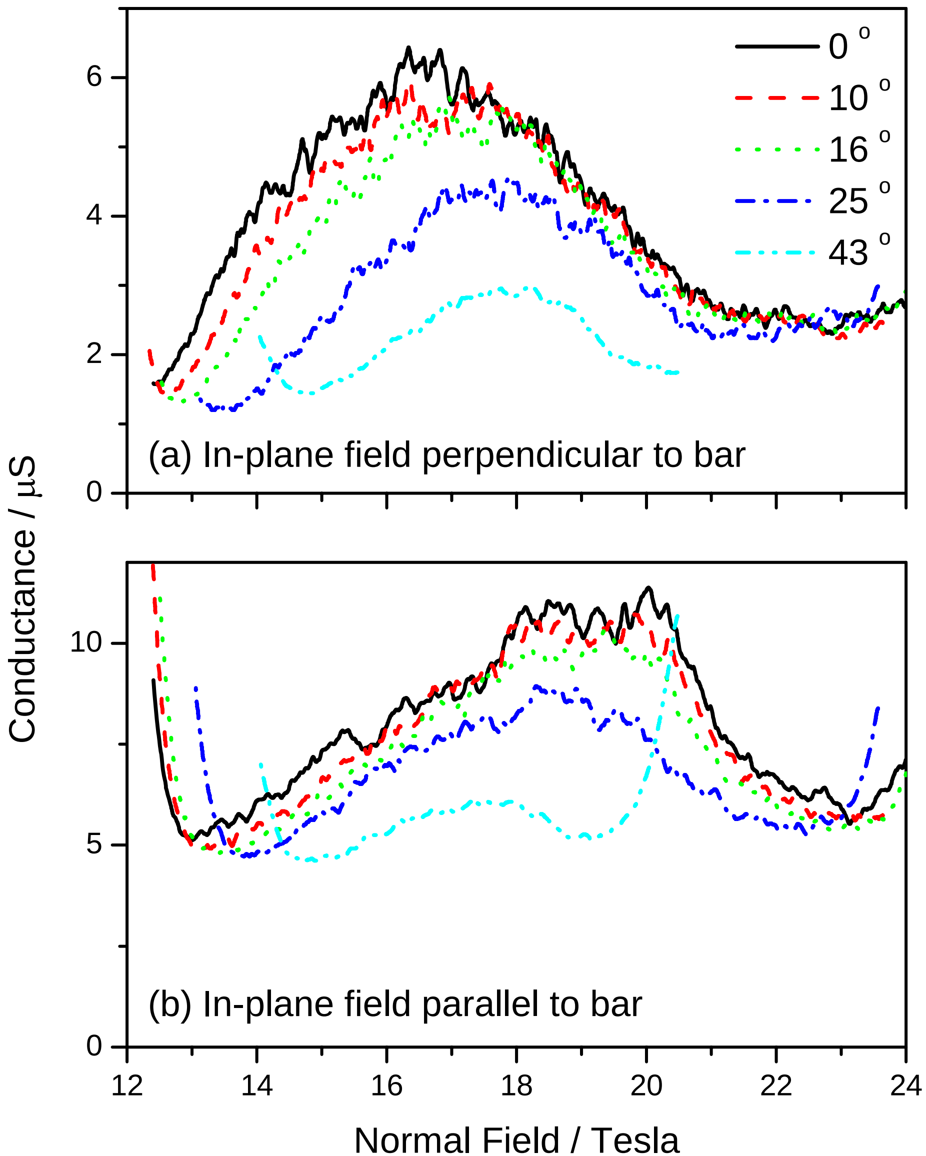
2 Contact Length and Width Dependence





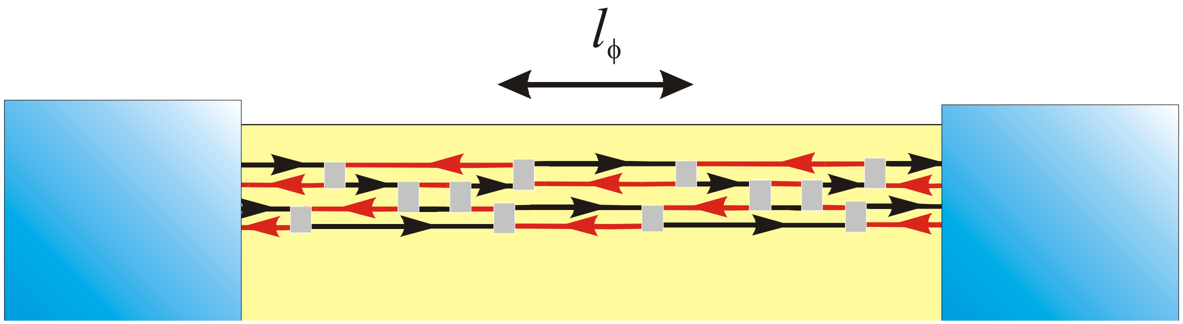


In-plane field + 2-Contact Bars



- Background changes smoothly.
- Minima at high and low field regions.
- Conductance decreases with in-plane field.
- Small fluctuations change completely from one angle to next.
- Fluctuations decreases as conductance decreases.

Universal Conductance Fluctuations

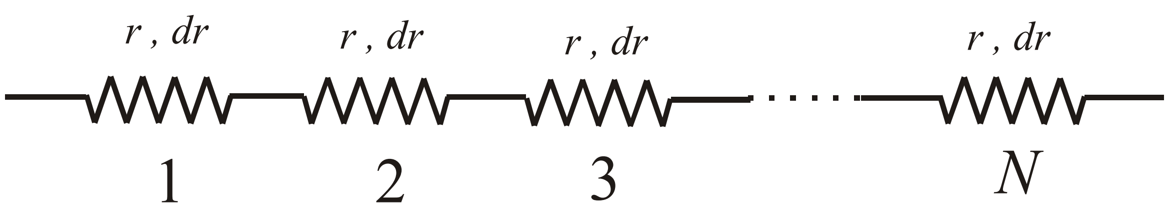


- Phase coherent sections contribute e^2/h.

Universal Magnetoconductance Fluctuations

Sections of conductance g, fluctuates by dg ($= e^2/h$).

Add N resistors r in series. ($r = 1/g$)

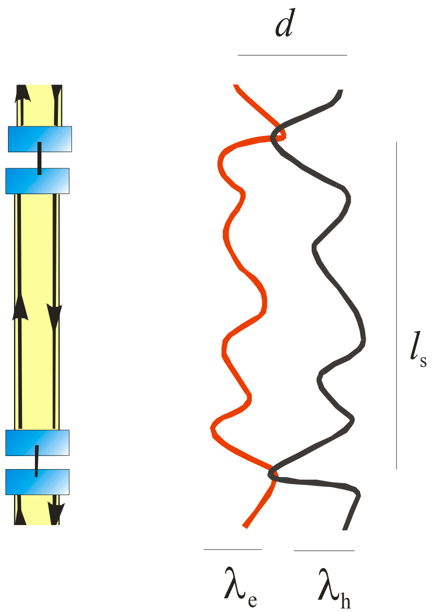


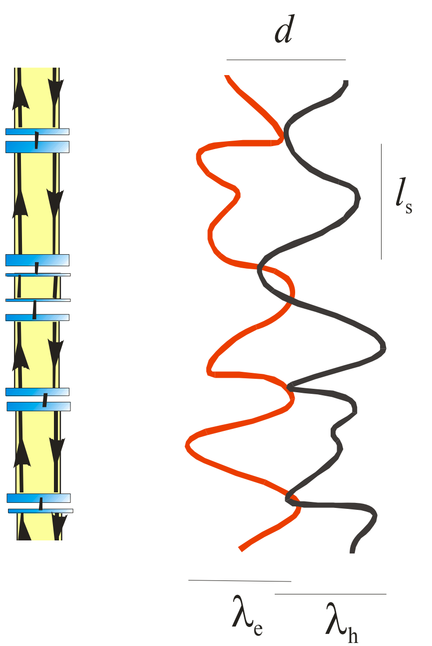
Total conductance, $G = g/N$

Total resistance, $R = Nr$, $dR = N^{1/2}dr$

$$dG = G^2 dR = G^2 N^{1/2}(dr/dg)dg = (G/g)^{3/2}dg$$

$$dG = (G/g)^{3/2}(e^2/h)$$

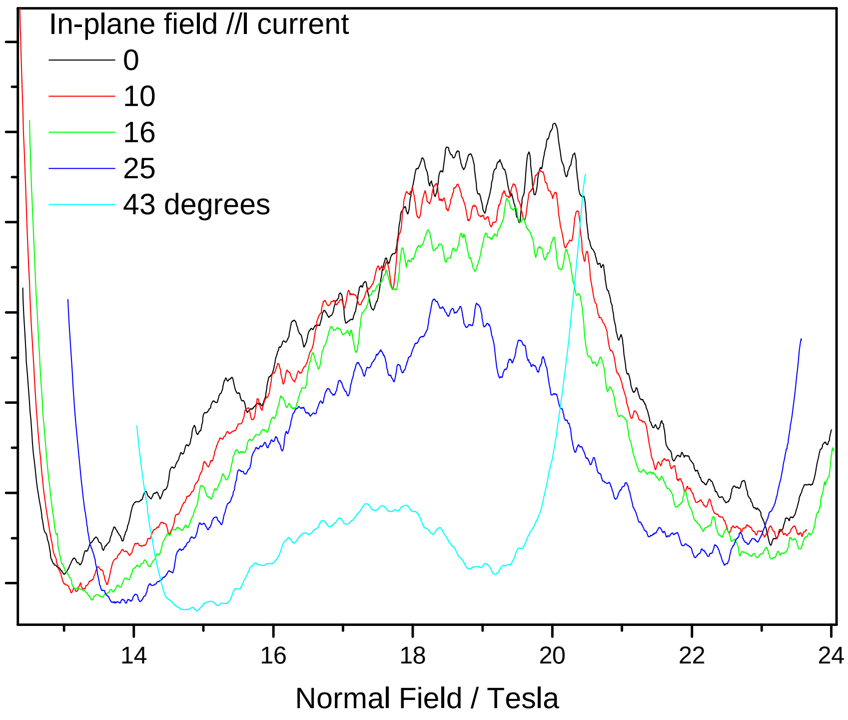


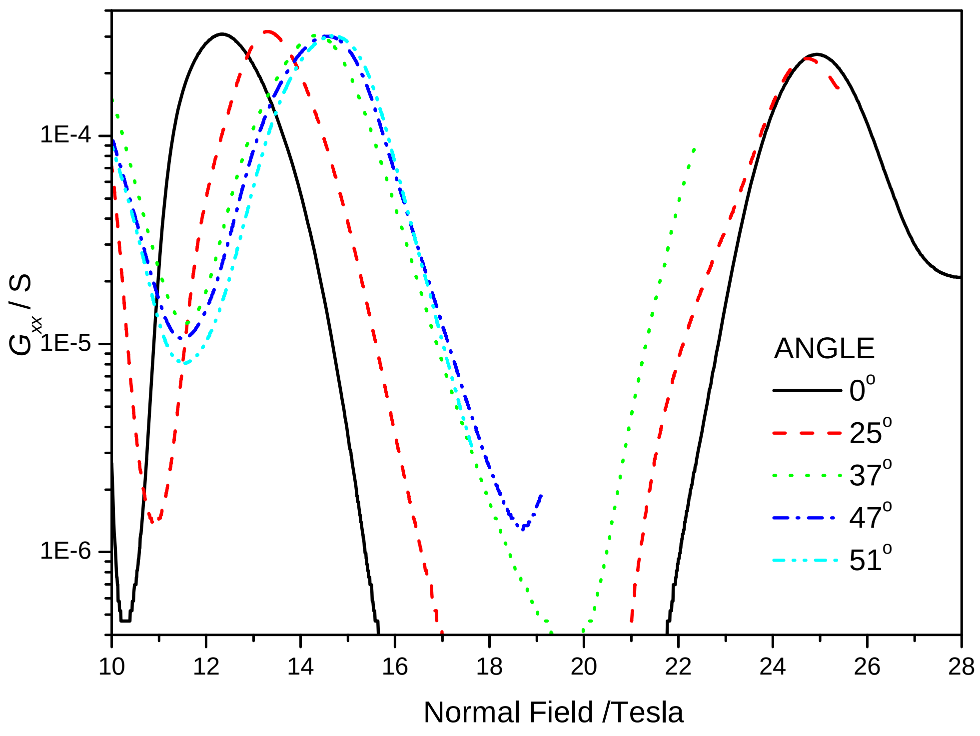


No. of sections change with field

- Length of section l_s is long if localization length λ is short.
- If each section has conductance *g*, *G* decreases as λ increases.
- I.e. G^{edge} is max. when σ_{xx} min.

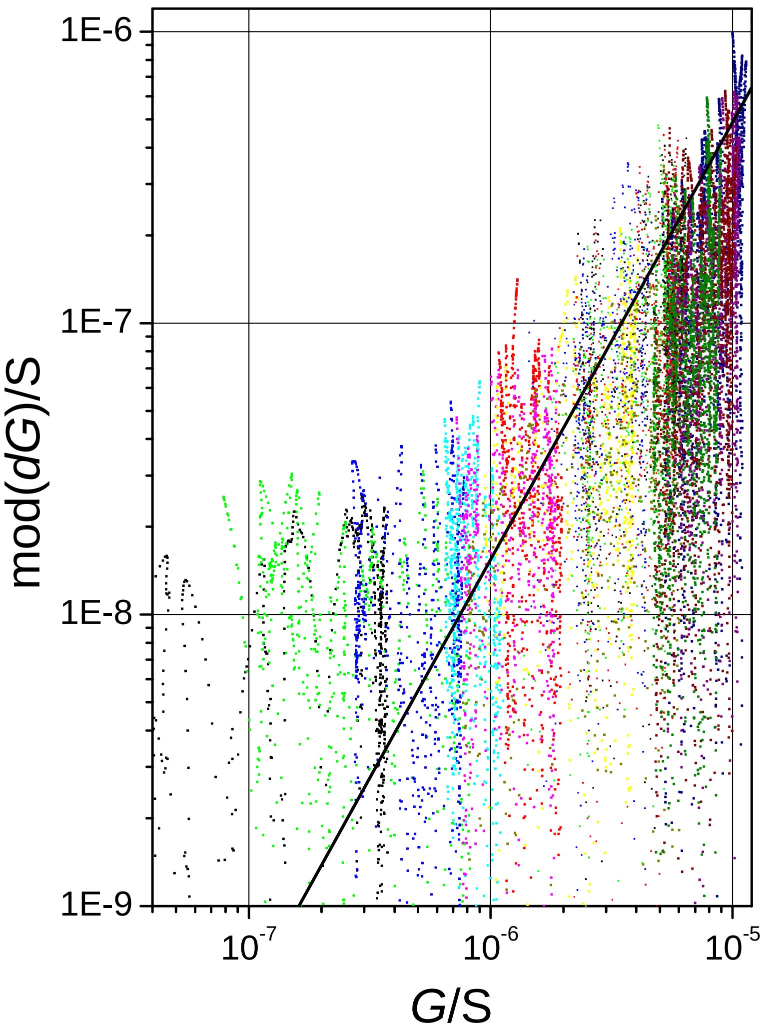
G^{bar} has opposite behaviour to σ_{xx}

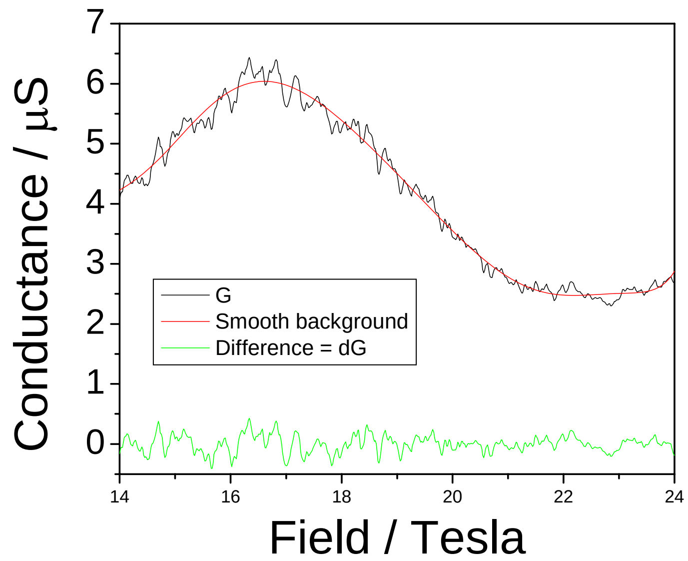




G^{edge} decreases as localization length increases - more, shorter sections

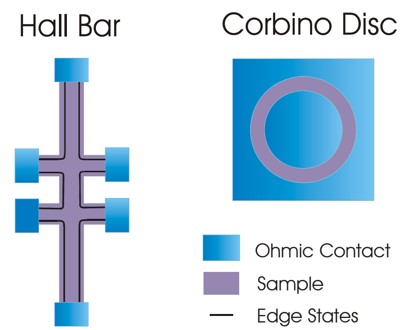
dG vs G



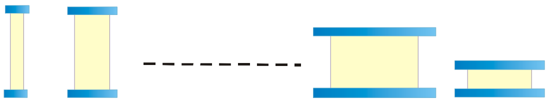


- All samples obey overall trend.
- $dG \sim G^{3/2}$ works well at large G. System well described as made up of characteristic sections of conductance g.

Summary of Insulating State



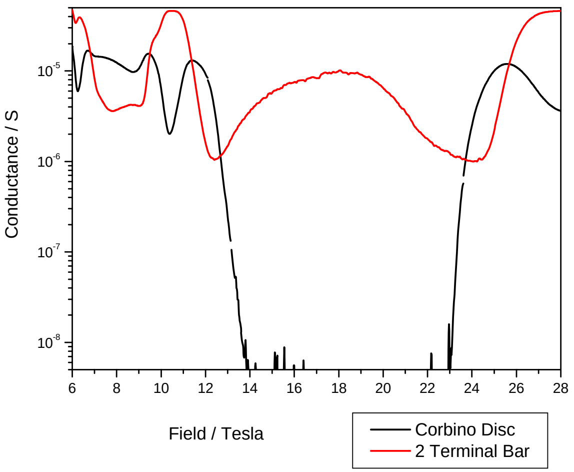
- Conduction dominated by edges.



- Fluctuations ~ UCF.

$$dG = (G/g)^{3/2}(e^2/h)$$

- G^{edge} has opposite behaviour to σ_{xx} due to interactions between e & h edge channels.



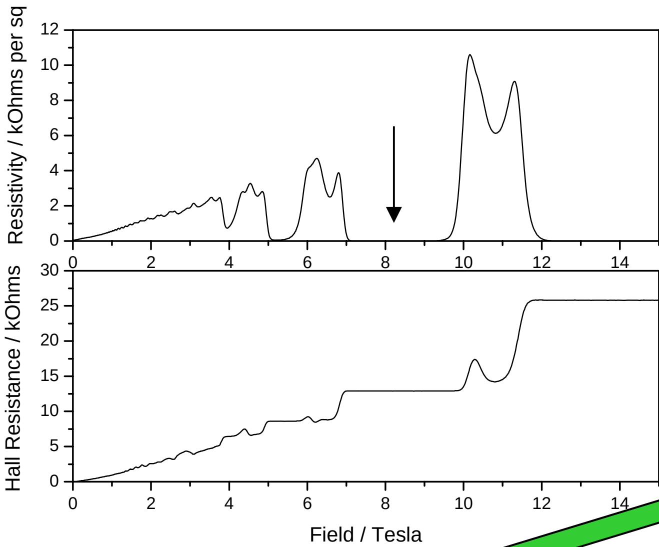
Compensated Quantum Hall Effect

How do ν_e-$\nu_\mathrm{h} = 0$ and ν_e-$\nu_\mathrm{h} \neq 0$ differ?

Current distribution? Are edges important?

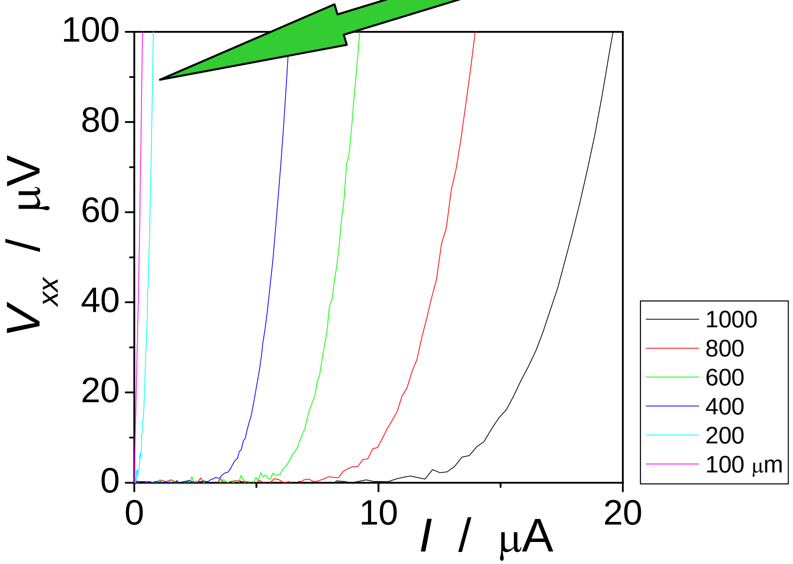
- Breakdown (current dependent) behaviour
- Width dependence

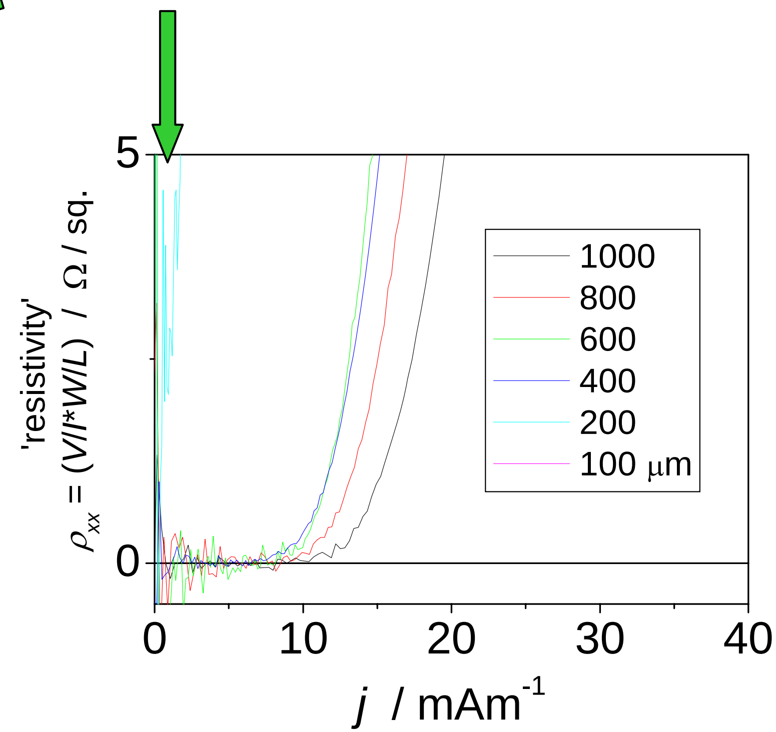
Larger I_c for $n_e : n_h \sim 2:1$



- Compare $\rho_{xx}(j)$

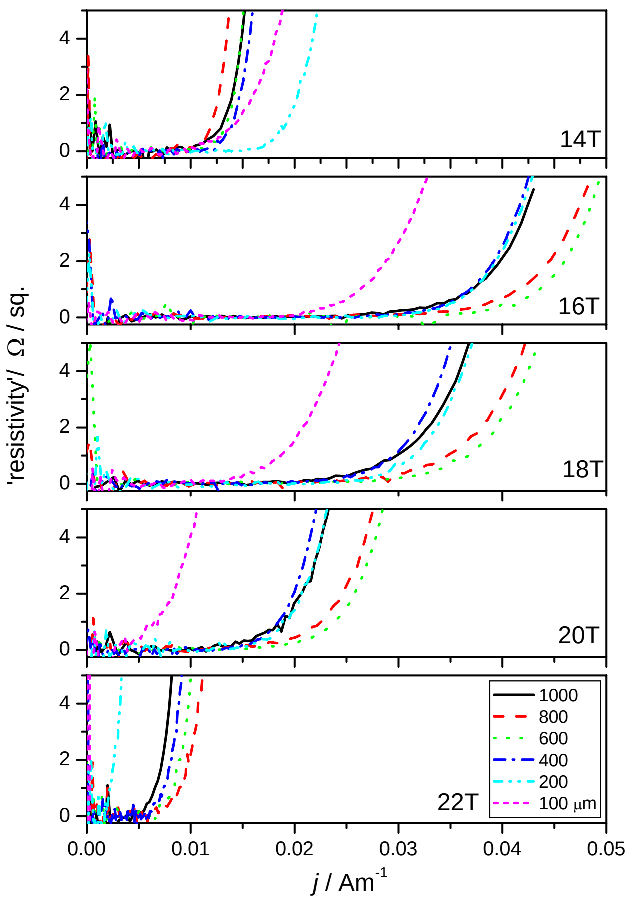
- 'Fragile' regime

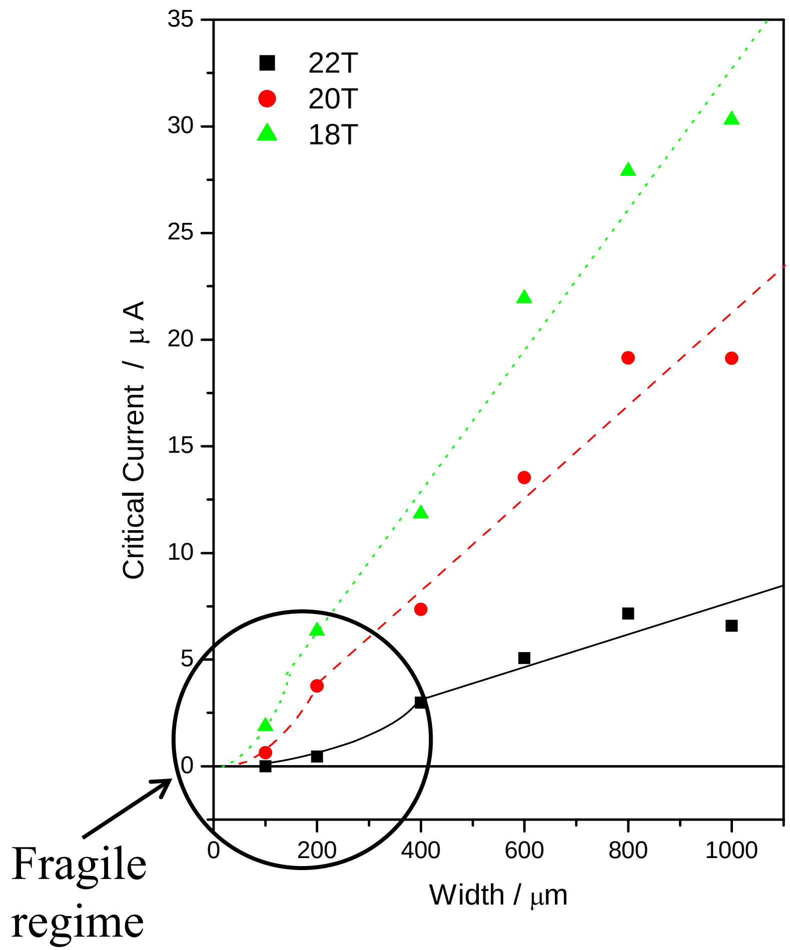




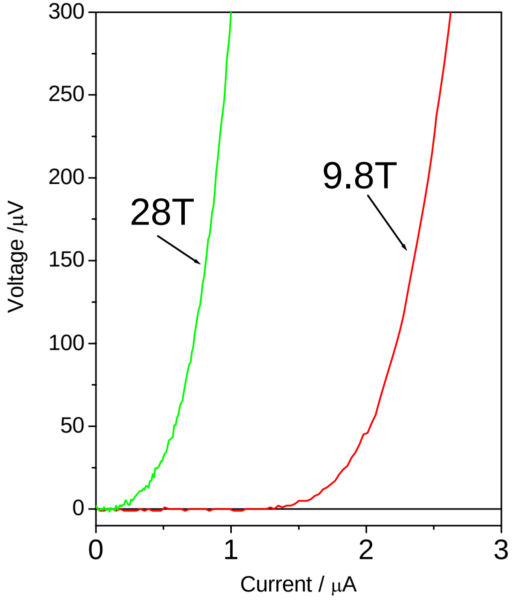
Magnetic Field Dependence

- W_c varies systematically with field





Closely matched n_e:n_h

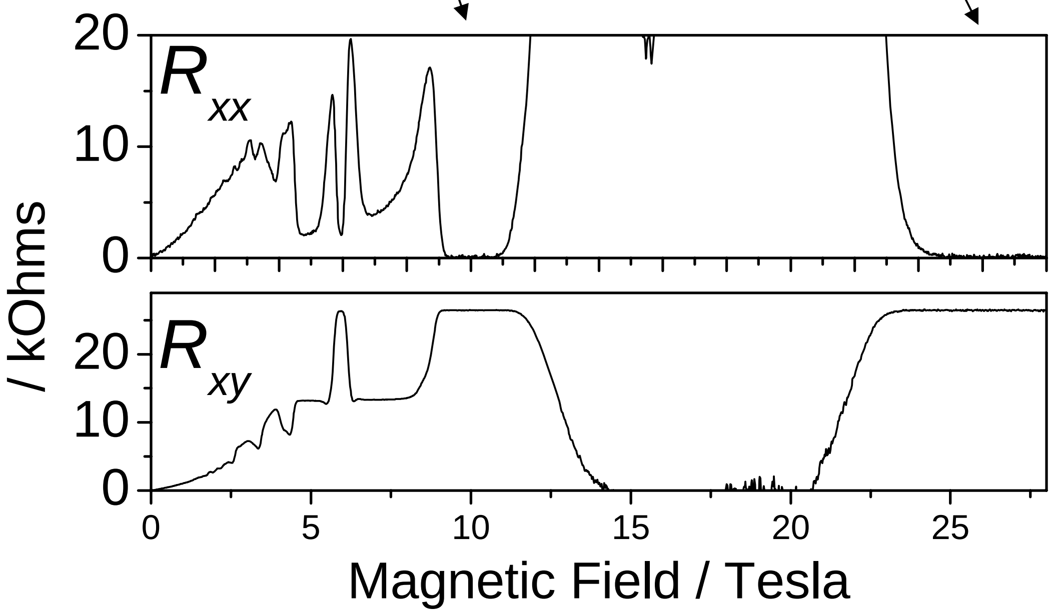


500 µm wide bar, $n_e = 6.3$, $n_h = 4.3 \times 10^{11} \mathrm{cm}^{-2}$

50 mK. Define $I_c = I_c(V_{xx} = 20\ \mu V)$

(Rigal et al, PRL 82 (1999) 1249)

$I_c = 1.7 \mu A$ $I_c = 0.3 \mu A$



Kawaji et al. J. Phys. Soc. J, 63 (1994) 2303

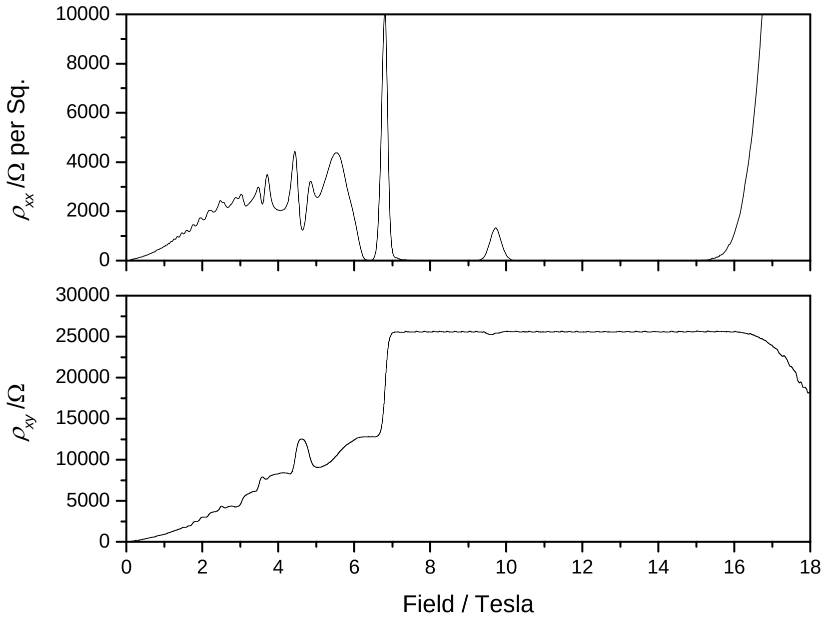
170µA, 120µm n-type GaAs/(AlGa)As ν=2, 10T

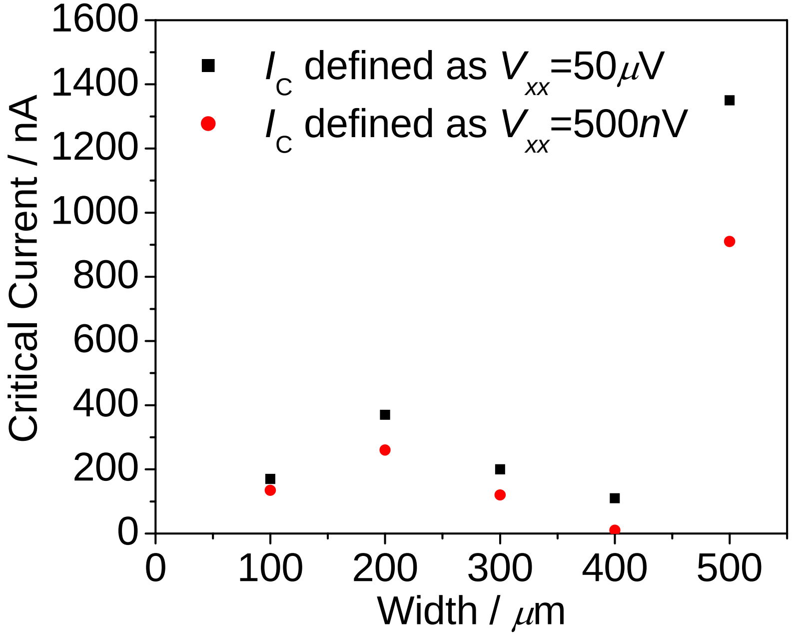
Stoddart et al. Microelectronic Engineering 47 (1999) 35

9.2 µA , 200µm p-type GaAs/(AlGa)As ν=1, 4.4T

Width Dependence: even 400 μm bar is 'Fragile'!

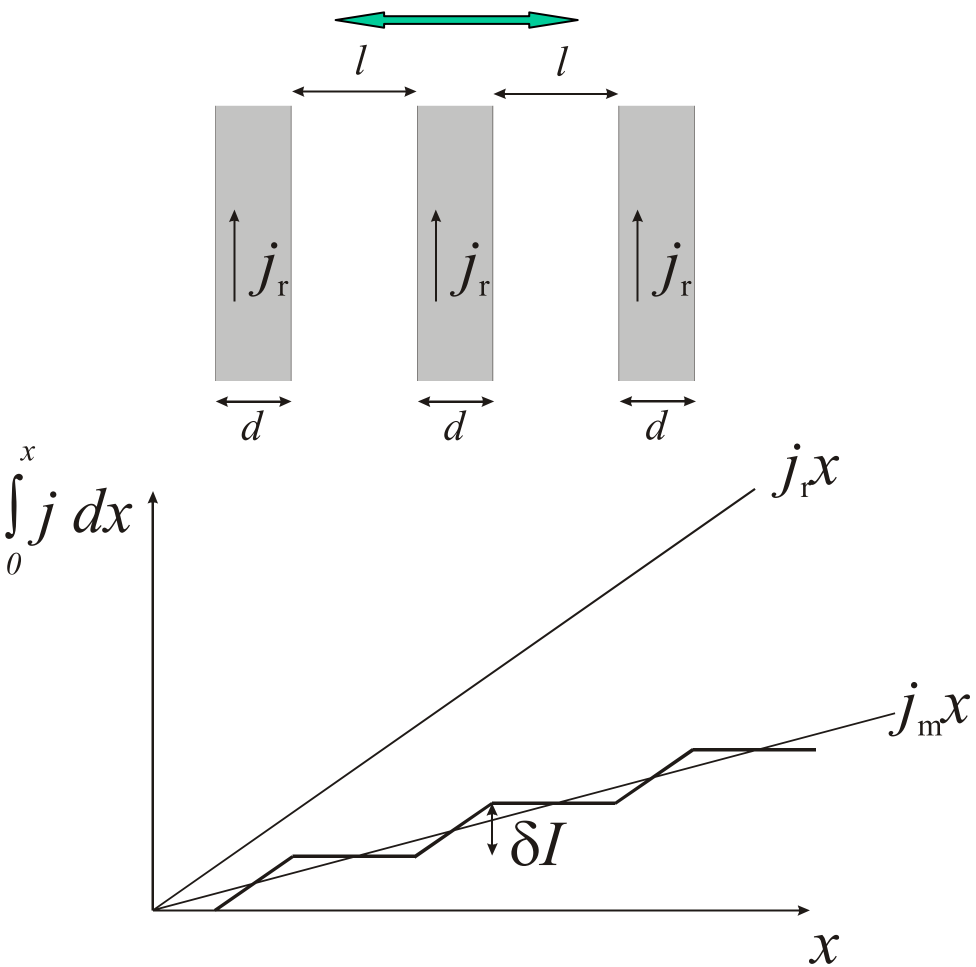
$n_e = 8$, $n_h = 5.2 \times 10^{11}\,\mathrm{cm}^{-2}$



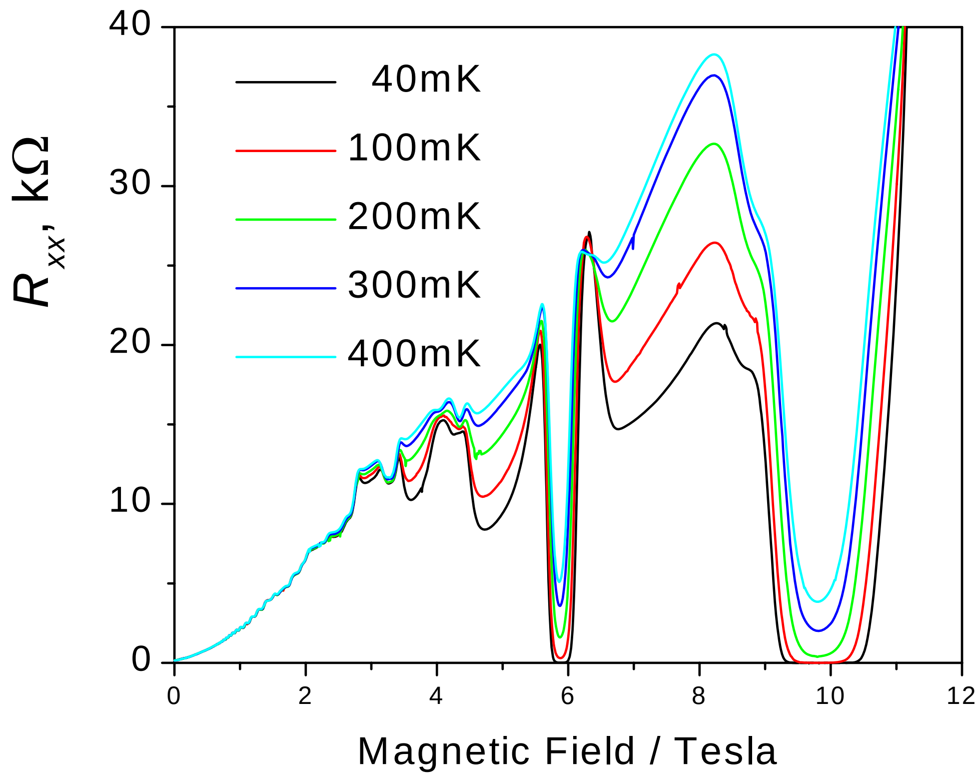


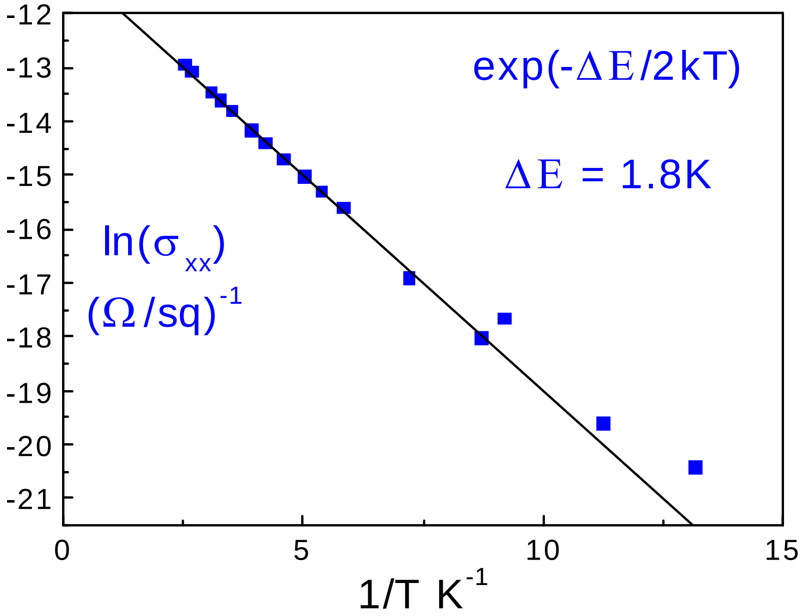
• Small I_c, sensitive to disorder

'Fragile' regime once width is comparable to wide disordered regions: critical width W_c



Compensated Quantum Hall Effect





Conductivity has a very small activation energy

Breakdown Summary

- Ohmic width dependence for wide samples
- Fragile behaviour for 'narrow' samples
- W_c depends on E_F and E(LL) (B dep.)
- Strong influence of disorder when I_c is small

Current flowing in sample interior, inhomogeneous on a scale W_c.

Summary

ν_e-$\nu_h = 0$ Insulating States

- $\sigma_{xx} = 0;$

  $\sigma_{xy}^{net} = \sigma_{xy}^{e} + \sigma_{xy}^{h} = 0$

- Current carried by edge-channels, dominating behaviour

- Interior totally insulating

ν_e-$\nu_h \neq 0$ 'Metallic' States

- $\sigma_{xx} = 0;$

  $\sigma_{xy}^{net} = \sigma_{xy}^{e} + \sigma_{xy}^{h} \neq 0$

- *W* dependent current dependence

- Current in sample interior